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EFFICIENCY IMPROVED TURBOPROP

W. S. Gearhart

Technical Memorandum
File No. 82-124
10 June 1982
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# REPORT DOCUMENTATION PAGE

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Renewed attention has been focused on the efficiency of aircraft propulsion as the cost of fuel has risen. Studies conducted by NASA [1] to obtain fuel efficient aircraft have considered relatively highly-loaded turbo-prop systems. The disc loadings of these propellers are as much as four times higher than those on present turboprop aircraft. The higher disc loadings result in greater slipstream swirl and higher energy losses. Of primary importance is the radial distribution of the energy losses across the slipstream due to the tangential and axial velocities. This study presents

20. the results of analysis defining the various sources of energy loss resulting from a swirling slipstream downstream of a propeller. Experimental data are presented demonstrating the presence of such losses and a propeller configuration discussed which offers improved propulsive performance when relatively highly-loaded propellers are employed.

Subject: Efficiency Improved Turboprop

References: See page 13.

Abstract: Renewed attention has been focused on the efficiency of aircraft propulsion as the cost of fuel has risen. Studies conducted by NASA [1] to obtain fuel efficient aircraft have considered relatively highly-loaded turboprop systems. The disc loadings of these propellers are as much as four times higher than those on present turboprop aircraft. The higher disc loadings result in greater slipstream swirl and higher energy losses. Of primary importance is the radial distribution of the energy losses across the slipstream due to the tangential and axial velocities. This study presents the results of analysis defining the various sources of energy loss resulting from a swirling slipstream downstream of a propeller. Experimental data are presented demonstrating the presence of such losses and a propeller configuration discussed which offers improved propulsive performance when relatively highly-loaded propellers are employed.

Acknowledgement: This work was supported by Naval Sea Systems Command, Code NSEA-63R31.

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## Nomenclature

| | |
|---|---|
| $V_\infty$ | forward speed of craft |
| $V_\theta$ | tangential component of velocity |
| $U$ | peripheral velocity of propeller |
| $U_T$ | tip velocity of propeller |
| $R_P$ | propeller radius |
| $A_P$ | propeller disc area |
| $A_S$ | slipstream cross-sectional area |
| $g$ | gravitational constant |
| $J$ | advance ratio $\left(\frac{V_\infty}{n\ D_P}\right)$ |
| $\gamma$ | density of fluid |
| $P_\infty$ | free stream static pressure |
| $Q$ | volumetric flow rate |
| $D_P$ | propeller diameter |
| $n$ | shaft speed (rps) |
| $\rho$ | mass density of fluid $\left(\frac{\gamma}{g}\right)$ |
| propulsive efficiency | $\frac{(\text{Thrust})(V_\infty)}{\text{Shaft Power}}$ |
| $T$ | thrust |

## Introduction

The function of any propeller system is to provide a forward thrust along its axis. The design objective is to obtain a maximum propeller thrust with a minimum required shaft power while satisfying the practical limits of propeller size and shaft speed. The generation of thrust requires that some kinetic energy be lost in the propeller slipstream. These losses are associated with both axial and rotational velocity components in the slipstream. In addition, the presence of rotational velocity in the slipstream results in a low pressure region in the far wake which reduces the net effective thrust generated by the propeller. Propellers that ingest large mass flows and place a small amount of energy per unit mass in the flow have a relatively small amount of slipstream swirl. However, the trend now is toward more heavily loaded propellers, having lower shaft speeds and heavier blade loadings. Thus, a reevaluation of the relative magnitudes of the losses associated with the velocity components in the propeller slipstream is necessary.

The present analysis will consider only an ideal efficiency, i.e., an inviscid, incompressible fluid is assumed and frictional losses on blading or ducting associated with the propeller are neglected. On this basis, and within the assumptions stated for the cases considered, the propulsive coefficients obtained are the highest that can be expected. Naturally, the inclusion of real fluid effects will lead to lower values than are indicated herein. However, the inviscid analysis does provide a realistic evaluation of the energy losses in the slipstream as disc loadings and advance ratios are increased.

Sources of Losses in the Propeller Slipstream

The sources of energy loss in the propeller slipstream are shown in Figure (1) and consist of:

(a) tangential kinetic energy loss,

(b) axial kinetic energy loss, and

(c) a low pressure in the slipstream due to swirl which reduces the thrust of the propeller.

The tangential kinetic energy loss arises from the swirl component of velocity that is placed in the slipstream. As noted in Figure (1), which shows a typical radial distribution of swirl downstream of a propeller, the swirl velocity is highest near the axis of rotation. Therefore, greater gains in efficiency per unit mass of fluid can be achieved by removing the swirl near the axis of rotation.

The axial kinetic energy loss originates from the axial component of velocity which is typically greater than the forward speed of the ship over the outer portion of the slipstream. This is depicted in Figure (1) where the axial velocity is less than ship speed near the axis of rotation and greater than the ship speed over the outer half of the slipstream. The axial kinetic energy loss could be reduced if the axial velocity near the axis of rotation could be increased; thereby permitting a decrease of velocity in the outer region.

The third source of efficiency loss due to slipstream swirl arises from the lower than ambient pressure that must exist across the entire downstream face of the slipstream. By the radial equilibrium relationship the static pressure will be ambient at its outer boundary and continuously decrease to a minimum value at the axis of rotation. The radial equilibrium equation in conjunction with the swirl distribution can be used to obtain the static pressure distribution across the downstream face of the slip-

stream. Having obtained the static pressure distribution, it can be supplied over an increment of slipstream cylindrical area to obtain an axial force. The increments of force obtained in this manner can be summed over the entire slipstream to obtain the resultant axial force resulting from the static pressure distribution caused by the slipstream swirl. This force acts to reduce the thrust of the propeller. This low pressure region can be physically envisioned as a suction or drag force created by swirl that reduces propeller thrust for a given shaft horsepower. It will be shown in a later section that by reducing swirl near the axis of rotation the greatest gains in propeller efficiency can be achieved.

Figure (2) demonstrates how the existence of a lower than ambient pressure across the face of the downstream slipstream reduces the thrust produced for a given shaft horsepower. This is shown considering a control volume around a propeller and considering the momentum flux as well as the pressure forces operating on the control volume. Applying the radial equilibrium equation when the slipstream has swirl, the static pressure ($p_1$) is less than ambient ($p_\infty$) across the downstream face of the slipstream. The energy added per unit mass flow is the same in both cases, however the thrust produced by the propeller for a given shaft power, is reduced if swirl is present in the slipstream.

Some of the advanced propeller driven aircraft proposed for the 1990's are considering using pusher propellers located at the aft of the fuselage. This arrangement will result in the propeller ingesting the low momentum fluid from the hull and thereby provide an increase in propulsive efficiency. However, if proper design is not employed the interaction of the propeller blades with the shear flow from the fuselage will generate secondary flows which will result in higher than desired

swirl near the axis of rotation as discussed in [2]. The increased swirl near the axis of rotation, due to secondary flows, will increase the previously discussed energy losses and could offset the desired gains in efficiency obtained by ingesting the boundary layer from the fuselage.

In summary, the preceding indicates that the loss due to slipstream swirl can be most effectively reduced by reducing the swirl near the axis of rotation. In other words, if the angular momentum is removed from the flow over the inner portion of the slipstream it is possible to achieve larger efficiency gains than by removing it from the same percentage of fluid near the outer boundary of the slipstream.

Predicted Propeller Performance With Slipstream Swirl

An analytical model of a propeller and the energy losses associated with the slipstream is reported in [3]. From these studies it is possible to predict for a propeller with a given advance ratio and ingested mass flow or diameter, the magnitude of each of the previously described sources of slipstream loss as a function of propeller thrust coefficient.

It is reported by NASA in [1] that the advanced aircraft propellers will operate with a lower ratio of peripheral tip speed-to-forward speed, or higher advance ratio, than present propellers. The nominal value of tip speed-to-forward speed for conventional turboprops is 2.0 or greater, whereas the advanced prop-fans will approach 1.0. Predictions of propeller slipstream losses using the analysis of [3] applied to propellers of equal diameter but having a ratio of tip speed-to-forward speed of 2.0 and of 1.0, is illustrated in Figure (3). The increment of pressure drag derived and defined in [3] and shown in Figure (3) originated from two regions of

the slipstream. The first is the swirling slipstream outside the vortex core and the second is the vortex core region where solid body fluid rotation is approximated.

If a propeller thrust coefficient of 0.1 is required in both cases it is apparent that the losses associated with slipstream swirl are significantly greater for the propeller having the lower shaft speed. The lower shaft speeds are required to permit air speeds in the order of Mach 0.6 to 0.8 while preventing excessive blade surface velocities. The reduced blade surface velocities obtained by reduced shaft speeds minimize compressibility losses.

The significance of Figure (3) is that the axial kinetic energy losses did not change with advance ratio since the propeller diameter and ingested mass are essentially equal for the two cases. The energy losses associated the tangential kinetic energy losses and pressure drag increase by about a factor of four when the lower shaft speed is considered. The pressure drag term is the larger of the two energy losses resulting from slipstream swirl. Figure (3) indicates that about a 9.0 percent loss in efficiency is associated with the slipstream swirl at a thrust coefficient of 0.1. This closely agrees with NASA estimates of 8.0 percent in [1]. It is evident from this exercise that the losses resulting from slipstream swirl are highly dependent on the propeller thrust coefficient and advance ratio selected in the design.

The approach described in [3] for evaluating the losses due to slipstream swirl is a one dimensional analysis and assumes a free vortex loading on the propeller. A more general approach for obtaining the flow field through the propeller is by means of the streamline curvature flow field analysis [4,5]. The fluid properties of pressure and velocity are

derived at selected stations for an arbitrary spanwise loading and the streamlines through the propeller are obtained. A nonuniform total energy inflow to the propeller such as caused by the boundary layer on the fuselage can be used in this solution. A control volume is specified as illustrated in Figure (4) and the momentum analysis applied to obtain the net effective thrust generated by the propeller for a given shaft horsepower.

The analysis can be applied to a propeller configuration where stator vanes are placed either upstream or downstream of the propeller. If placed in front of the propeller they would introduce counterswirl into the flow, or if placed aft of the propeller they would remove swirl placed in the flow by the propeller. This technique will permit predictions of performance with stators having varying lengths of span relative to the propeller and which impart angular momentum or torque which is some fraction of that supplied by the propeller. The results are plotted as shown in Figure (5) and indicate what span of stator blades are required relative to the propeller to obtain a given increase in efficiency over that of the propeller alone.

Experimental Evidence of Reduced Propeller Thrust Due to Slipstream Swirl

The pressure effects of swirl in the slipstream, especially near the axis of rotation, were experimentally demonstrated in [6]. A back-up bar was located behind the propeller hub and supported by a separate strut as shown in Figure (6). The back-up bar did not touch the propeller hub. Three propellers with different operating advance ratios and, hence, different amounts of slipstream swirl, were tested with this arrangement. When the back-up bar was in place, the shaft thrust was increased for two propellers by almost 20 percent and for the other one propeller by better than 30 percent as compared with the propeller-alone cases. The shaft torque was unchanged for each propeller with and without the back-up bar in

place. As a check on this measurement, the back-up bar was removed and a conical tailcone was installed. This tailcone was supported by a separate strain-gaged shaft located inside the propeller drive shaft. The axial force, or drag, measured on the tailcone was equal to the amount that the shaft thrust was increased with the back-up bar in place. The net axial force transmitted to the body, in this case, via both shafts was $(T - \Delta T)$. When the back-up bar was in place, the net axial force transmitted to the body was $(T + \Delta T)$. This experiment demonstrates that the pressure effects of swirl contribute to the reduced thrust of the propeller. The shaft power required at a given shaft speed did not change with the presence of the back-up bar or the strain gaged tailcone.

The experimental measurements described above suggest that significant gains in efficiency can be achieved by elimination of the swirl near the axis of rotation. Experimental LDV measurements across the slipstream of two separate propellers are reported in [7]. These propellers were tested in a water tunnel and were driven by an upstream dynamometer. The measured tangential velocity is shown in Figure (7). Applying the radial equilibrium equation and obtaining the static pressure distribution across the slipstream, the radial distribution of pressure drag is obtained as indicated in Figure (8). It is apparent that nearly one-half of the energy loss associated with the pressure drag could be recovered if the swirl were removed from the inner 0.4 diameter of the slipstream.

The use of short-span stators permitting the inboard sections of a propeller to carry a heavier loading has a number of benefits. First it will permit the use of propellers of smaller diameter which result in reduced noise. The use of inboard loading reduces blade surface velocities near the tip which also reduces noise as reported in [1]. The application

of such an arrangement to a pusher type propeller located at the aft of an aircraft permits placing higher energy into the low momentum fluid from the fuselage which will increase propulsive efficiency as described in [3].

Proposed Propulsor Arrangement for Aircraft

The prior art in aircraft propulsion has included patents granted for stationary vanes mounted either fore or aft of the propeller. Counterrotating propellers have been considered as well having stationary appendages such as the wing or the elevator and direction control surfaces which act as stator vanes. Their success and application have been limited by their mechanical complexity. The added drag and weight associated with such arrangements have also been prohibitive. Interference with controllable pitch propeller performance at other than design conditions has also prevented any practical adaptation. These reasons, in addition to the relative lightly loaded propellers used in the past and the small gains that could be achieved if the swirl in the slipstream were removed, have provided cause for not applying a stator system.

It is proposed that a stator arrangement be considered as illustrated in Figure (9). In this arrangement a series of short span stators are mounted on the nacelle of a tractor type propeller. Figure (10) depicts the short-span stator arrangement for a tractor and pusher type propeller application.

The primary advantage of the short-span stator arrangement is that the surface area and weight associated with such an arrangement is minimized, while the slipstream swirl is removed from a region where the greatest gains in efficiency are achieved. In so doing, the noise performance is also improved since tip loadings are reduced. The small span of the stator relative to the propeller should permit the use of controllable pitch

propellers with little effect on their performance. The small planform area of the stator system should have minimal effect on the maneuvering, stability and control of the aircraft.

The use of such a stator system permits a larger portion of the propeller blade loading to be carried inboard which will increase propeller efficiency and reduce propeller noise. The use of the proposed arrangement permits efficient operation with a smaller diameter propeller. A reduced diameter propeller could be of equal efficiency but have improved noise performance, reduced weight and be structurally more acceptable. Alternately, the use of the stator system would permit designing for lower shaft speeds resulting in lower blade surface velocities which would reduce noise and compressibility effects.

In summary, if slipstream swirl is to be removed it is proposed to do so in that region where the largest gains in efficiency and noise performance can be achieved. The use of a short span stator system can accomplish this and minimize the adverse effects previously associated with counterswirl devices.

Based on a preliminary analysis, the overall gains that can be achieved with such an arrangement appear promising. Detailed design studies supplemented with experimental data are needed to fully explore the feasibility of the proposed arrangements.

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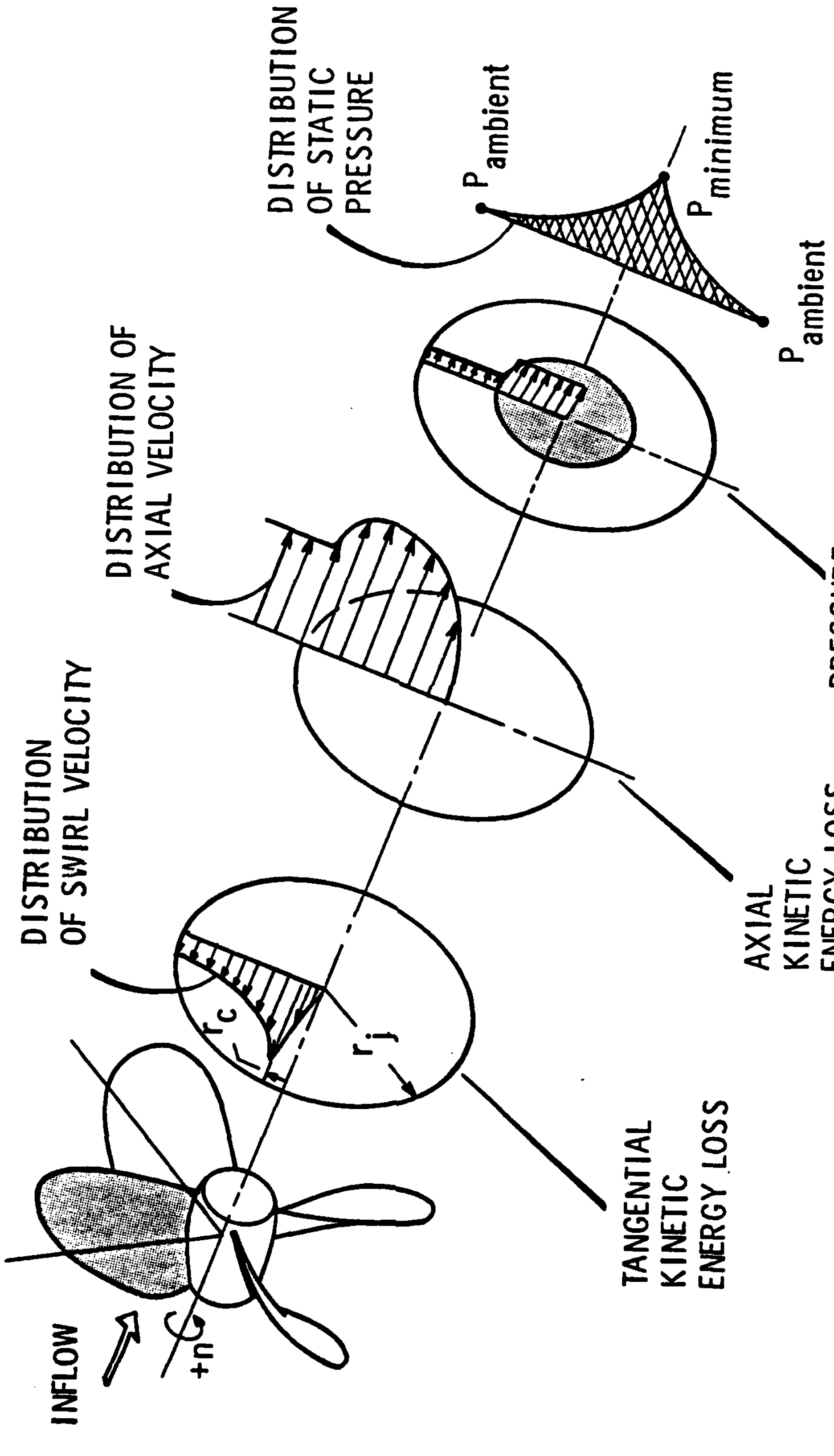


Figure 1. Sources of Energy Losses in the Slipstream

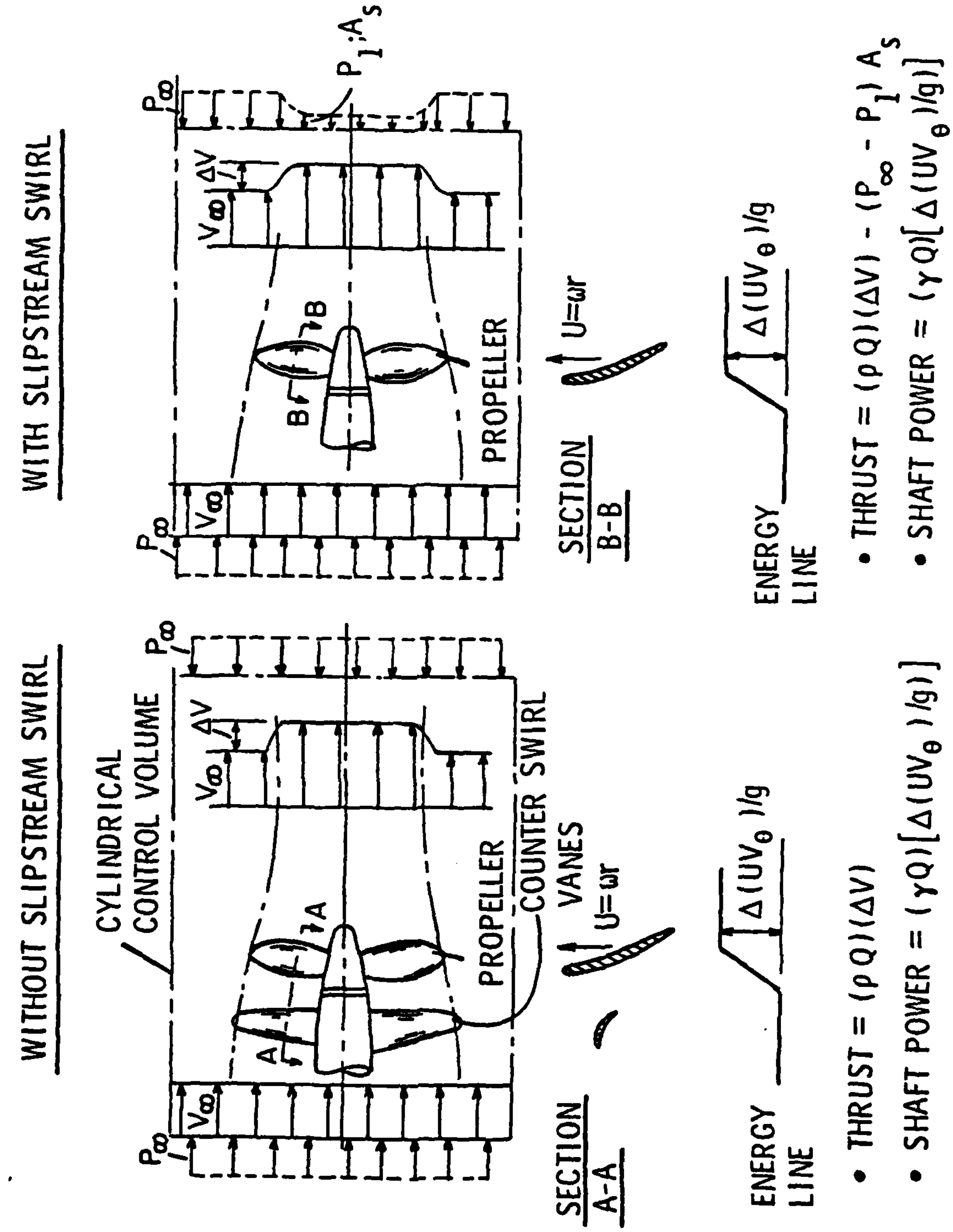


Figure 2. Reduced Propeller Thrust Due to Slipstream Swirl

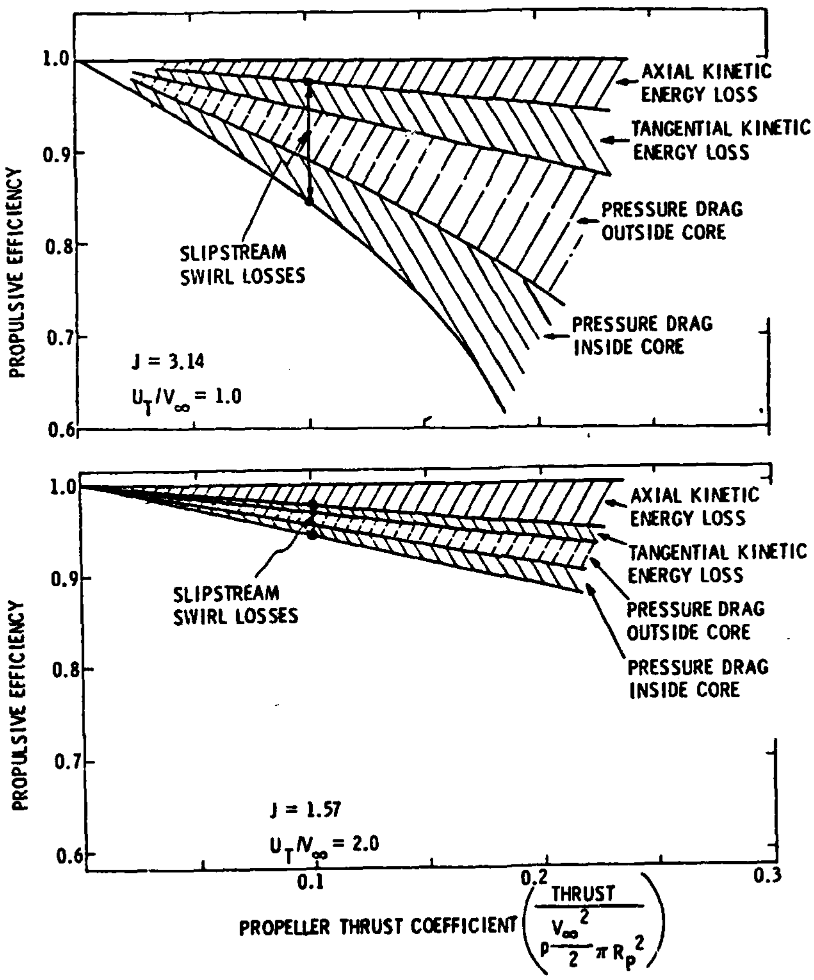


Figure 3. Energy Losses With Slipstream Swirl as a Function of Advance Ratio and Propeller Thrust Coefficient

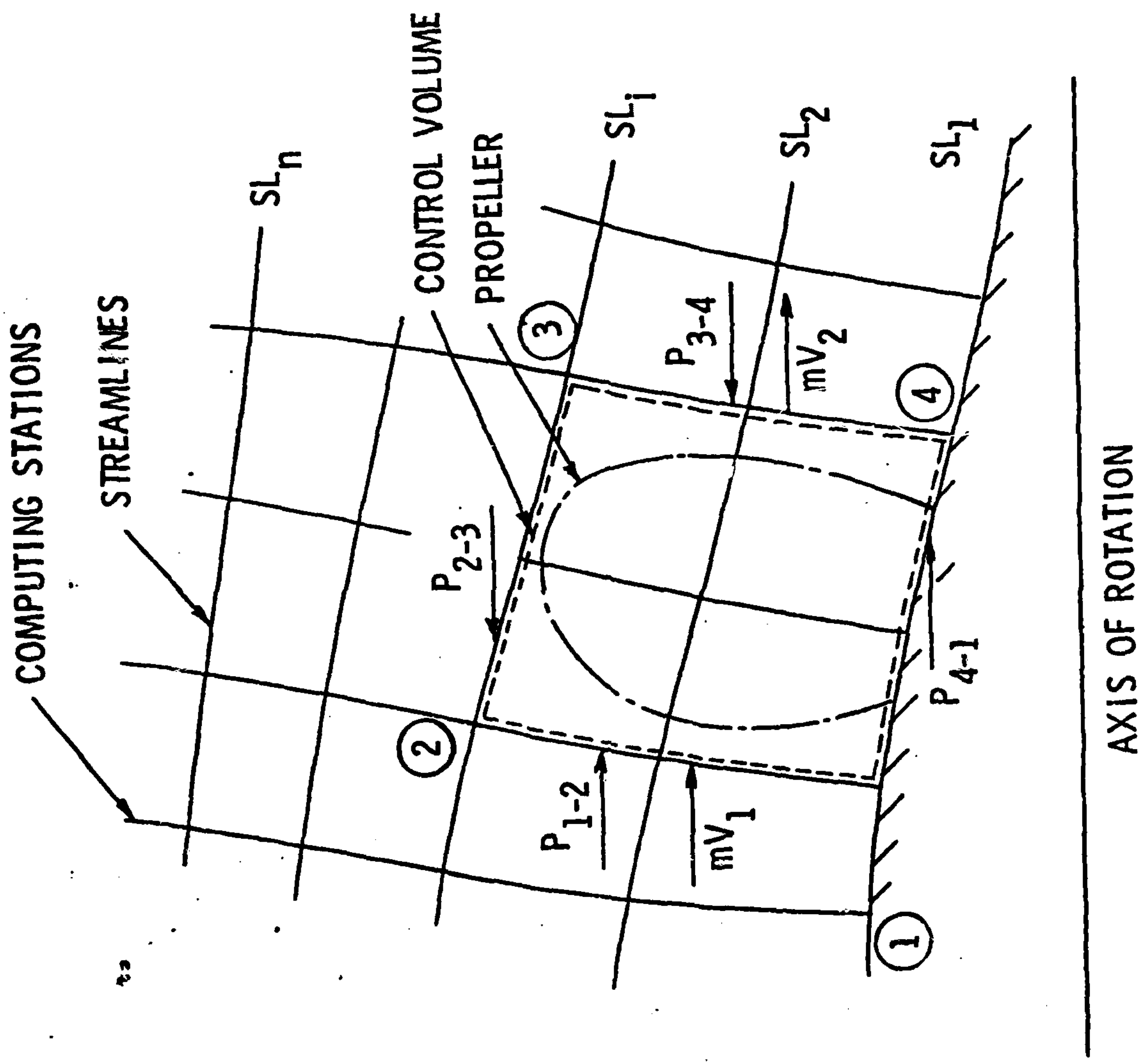


Figure 4. Streamlines and Control Volume Analysis to Determine Propeller Efficiency

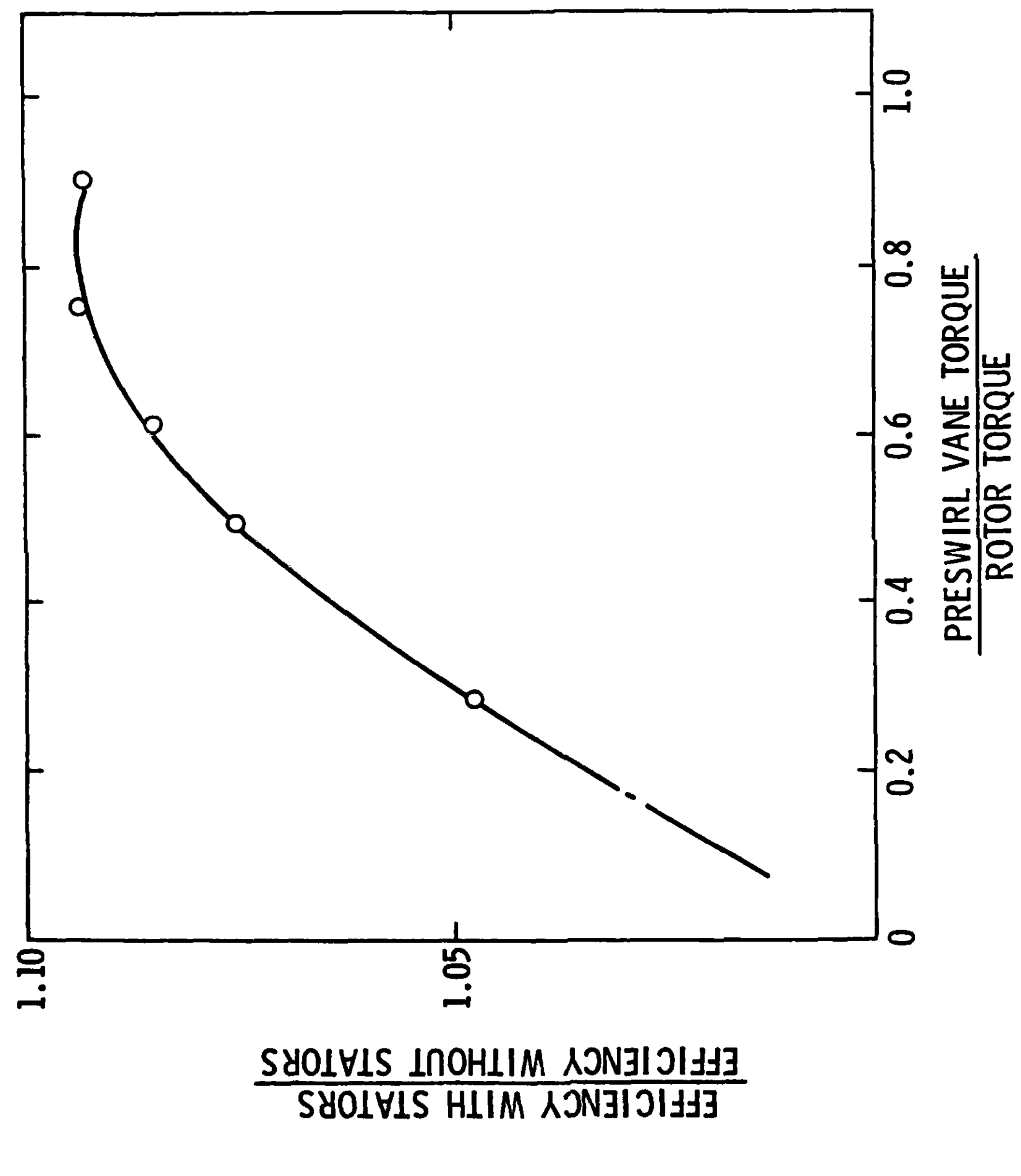


Figure 5. Propeller Efficiency as a Function of Counterswirl

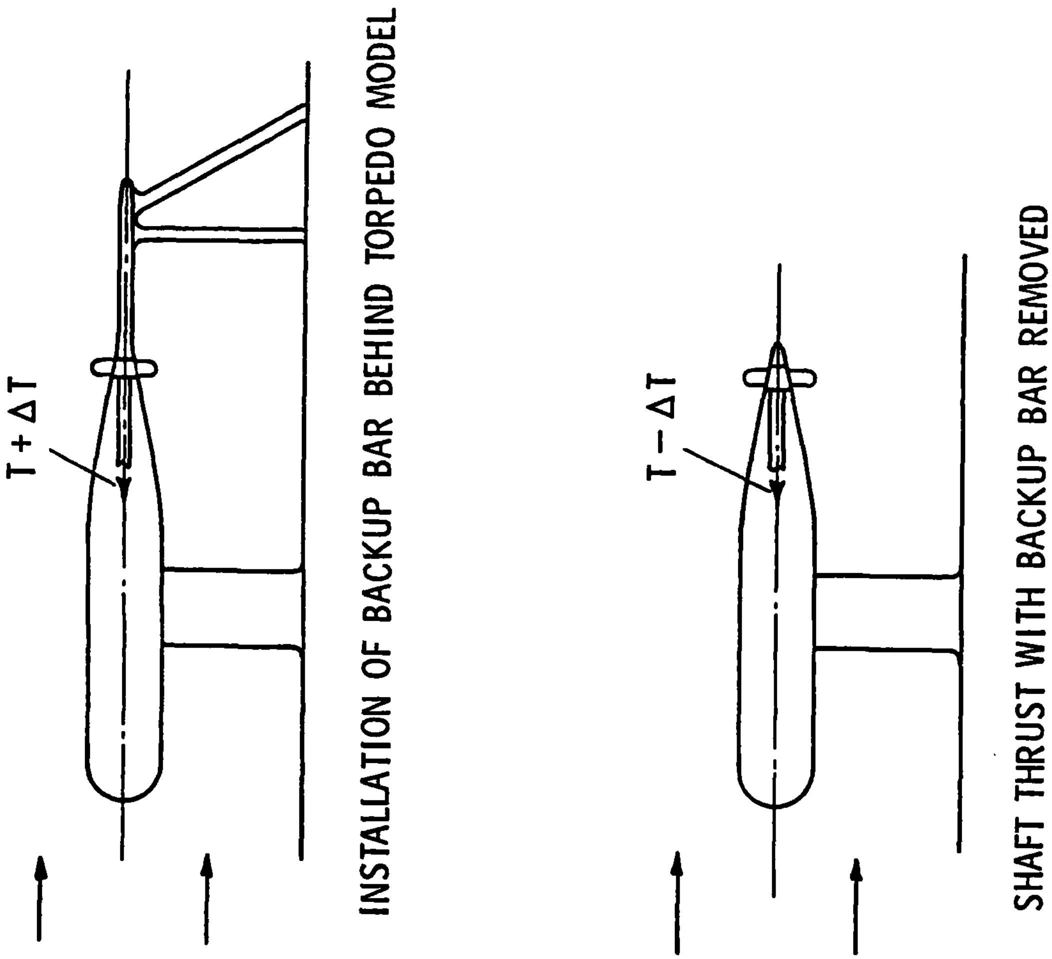


Figure 6. Experimental Demonstration of Pressure Drag

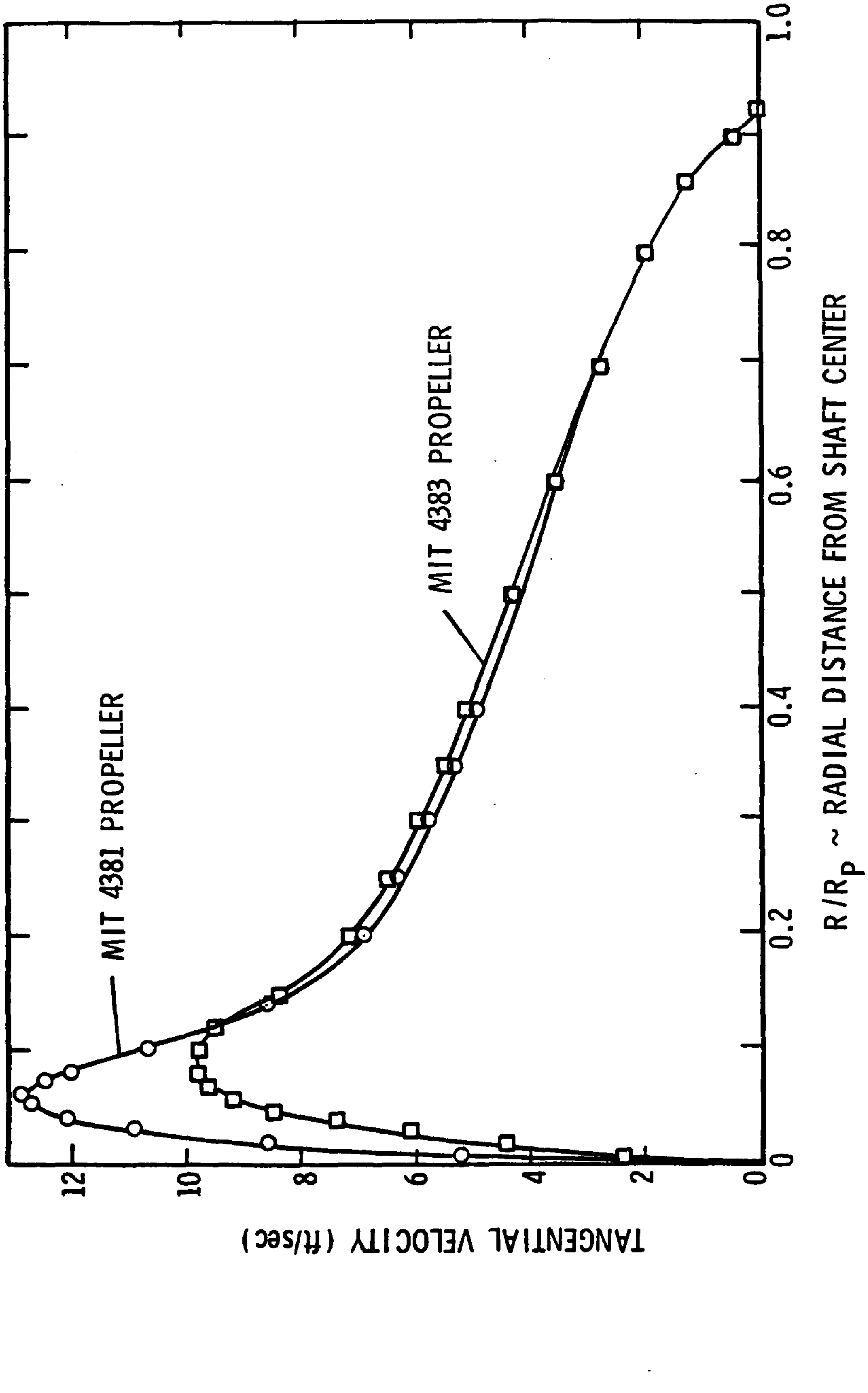


Figure 7. LDV Measurements of Tangential Velocities in MIT Water Tunnel

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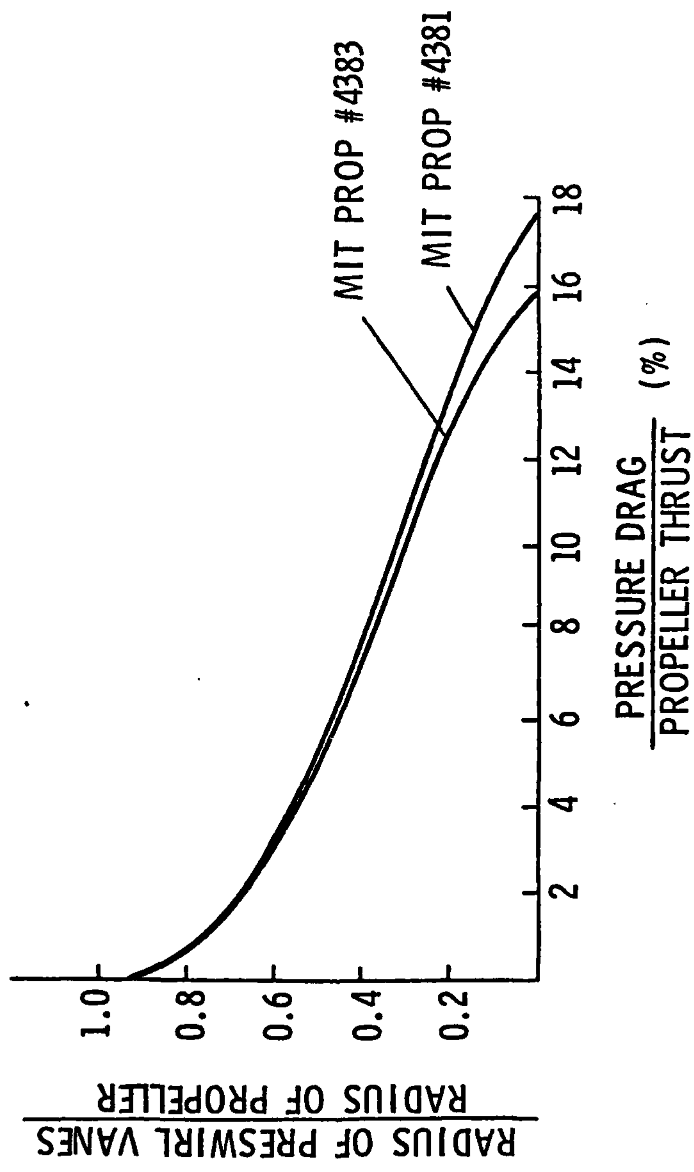


Figure 8. Radial Distribution of Pressure Drag Based on Experimental Tangential Velocities

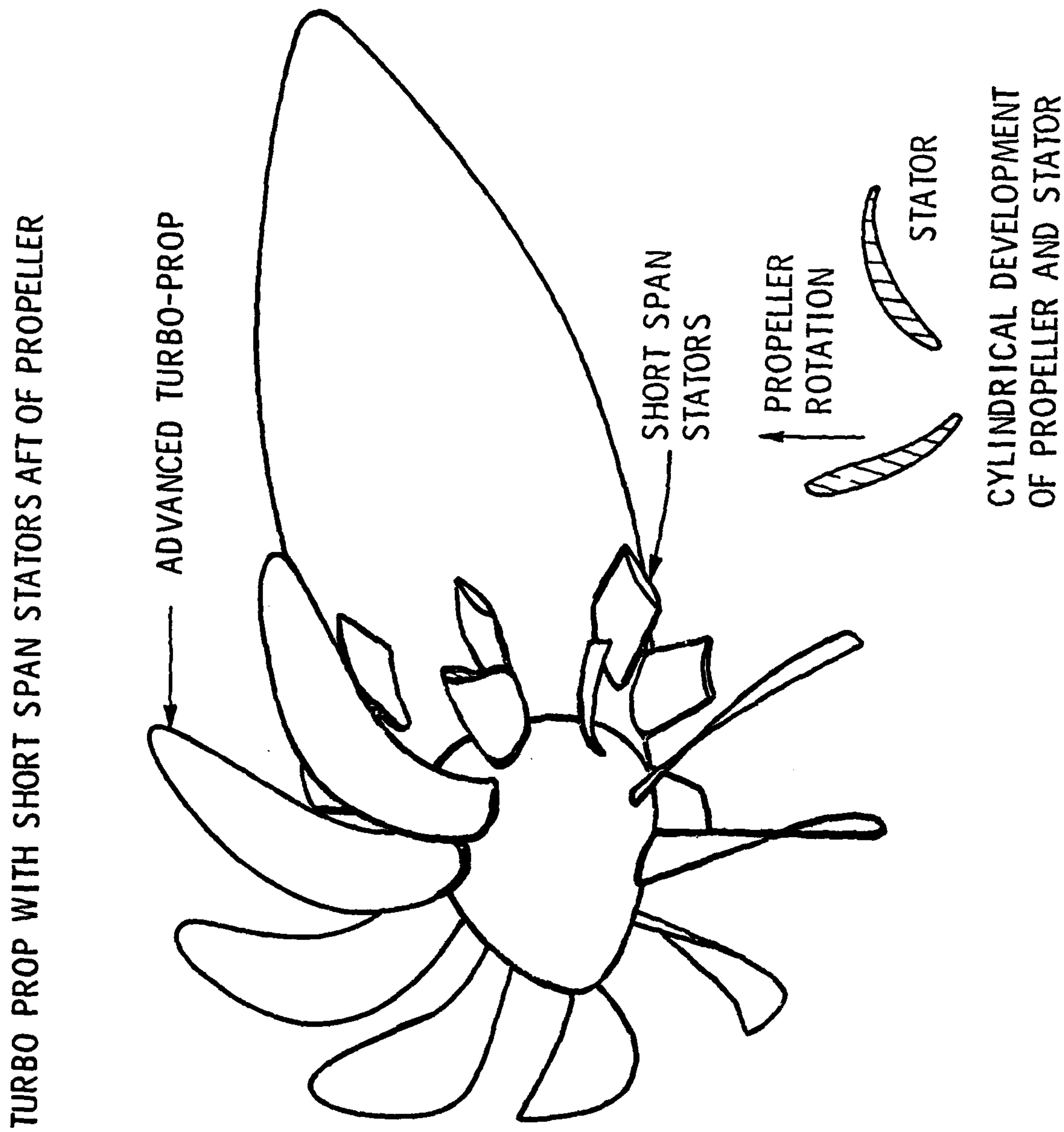


Figure 9. Short Span Stators on Nacelle of Tractor-Type Propeller

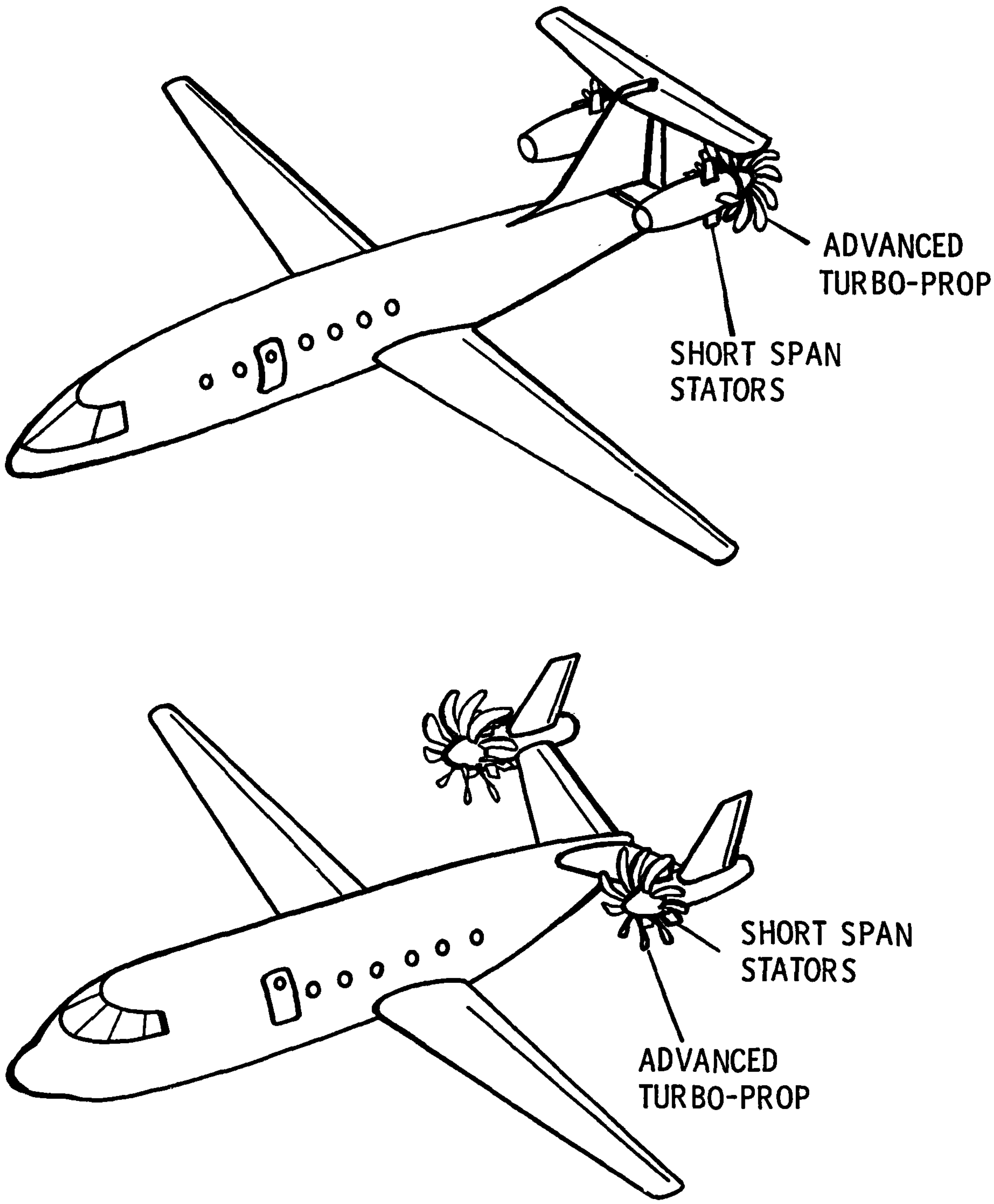


Figure 10. General Arrangement of Pusher Propeller and Tractor Type Propeller With Short Span Stator

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